Almond responses to a single-season of severe irrigation water restrictions

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Abstract

A substantial area of the new almond plantations in Spain are under irrigation but due to recurring severe droughts, the irrigation water allocation for agriculture can be drastically reduced eventually. This study assesses the physiological and yield effects of a single-season water deprivation (2017) over three seasons (2017-2019) on a previously well-irrigated mature almond [*Prunus dulcis* (Mill) D.A. Web, cv. Guara] orchard in southern Spain. Three irrigation treatments were imposed during 2017: full irrigation, applying the amount required to match maximum crop evapotranspiration (FI); sustained deficit irrigation applying 25% of FI (DI); and rainfed which received no irrigation at all (RF). During 2018 and 2019 all treatments were irrigated as FI. The results documents the vulnerability of irrigated almond orchards to severe water stress, as the rainfed treatment resulted in 92% tree mortality. In relation to FI, yield and quality were reduced in RF and DI by the negative impact of water stress on kernel weight and the formation of hull tights in the season of water deprivation. In the two following years, the negative impact on yields persisted due to reductions in fruit load (carry-over effects) even though trees in DI and RF were restored to full-irrigation levels. The three-year average yields of DI and RF treatments were less than what could be predicted from an almond production function

obtained in the same orchard. This highlights the long-term negative impacts that severe water stress resulting from suspending or reducing drastically irrigation in a single season has on almond trees.

Introduction

Almond cultivation is concentrated in Mediterranean climate areas around the world, with California, Australia and Spain producing 77%, 8% and 6 % of the world production respectively (International Nut and Dried Fruit Council 2019). In California and Australia, where irrigation water availability is commonly higher than in Spain, most of the orchards are irrigated to meet their maximum evapotranspiration (ET_C), with kernel yields above 2000 kg ha^{-1} (Almond Board of California 2019) and irrigation water requirements that can exceed 1300 mm (Goldhamer and Fereres 2017). By contrast, the acreage devoted to almond orchards in Spain has been traditionally dominated by low-yielding (c.a. 200 kg ha^{-1}) rainfed orchards located in marginal areas and characterised by low planting densities and canopy cover. However, a number of factors affecting almond world markets, including the recent California drought, has led to the expansion of intensive almond orchards under irrigation in Spain in the last decade. Irrigated almond plantations in Spain have been growing rapidly, reaching almost 140000 ha in 2020, 326% more than in 2014 (MAPA 2020). The production model adopted in Spain also targets average kernel yields above 2000 kg ha^{-1} and is based on the use of new varieties and rootstocks from European breeding programs; higher tree density on good quality soils; intensive fertilization and tree health measures; minimal pruning; and irrigation programs similar to those used in USA and Australia. The amounts of irrigation needed to meet ET_C can exceed 900 mm in Southern Spain (López-López et al. 2018a, b) but the use of deficit irrigation (DI) strategies are common in many areas limited by irrigation water availability (Moldero et al. 2021).

In most almond growing regions, but particularly in many areas of Spain, water is a scarce resource and irrigation water shortage is a chronic problem, so that deficit irrigation strategies (Fereres and Soriano 2007) must be applied. Tree water relations have been deeply studied in almond and it is well known that water stress affects stomatal conductance and CO_2 assimilation (Castel and Fereres 1982; Romero et al. 2004). Furthermore, the effects of water stress on tree growth and yield are also known. In this regard, yield is considered to be particularly sensitive to water stress in the periods of flowering, rapid vegetative growth in spring (Goldhamer and Smith 1995) and post-harvest (Goldhamer and Viveros 2000), while the kernel filling phase seems to be less sensitive (Romero et al. 2004; Girona et al. 2005). Based on this knowledge, DI strategies have been tested in almond by reducing irrigation applications from 30 to 60% of ETc (Romero et al. 2004; Girona et al. 2005; Egea et al. 2010, 2013; López-López et al. 2018b; Moldero et al. 2021).

An important problem arises when these regions are impacted by severe and persistent drought events that can cause substantial deprivations in irrigation water for agriculture. Irrigation water allotments can be drastically reduced to 20-30% of the historical levels for almond as it occurred in California during 2011-2016 (Doll and Shackel 2015) and in Australia during 1995-2007, or, in the worst case, reaching total cut-off, as it happened in Spain during the 1991-1995 drought. In severe drought situations growers have reacted with a number of measures including procuring additional irrigation water by purchasing water rights from other growers, extracting more groundwater or reducing demand by removing the older and/or less productive blocks of the orchard. Other practices such as reduction of evaporation losses (decreasing irrigation frequency) and severe pruning have been used as well. However, severe pruning has been shown to be ineffective as it leads to long-lasting effects of yield (Proebsting et al. 1981; Shackel et al. 2011).

Scientific literature only shows two studies where almond trees were subjected to severe water stress to investigate the effects of a severe water shortage due to a drought. First, Goldhamer and Smith (1995) imposed a single-season irrigation water deprivation on a mature 'Nonpareil' almond orchard in California. Treatments consisted of a control (FI) and four deficit irrigation strategies (406 mm; 36% of FI) differing in the temporal distribution of the deficits. Although there were no direct measurements of tree water status, the severe water stress suffered by trees caused a significative reduction in quality and yield during the season of the irrigation deprivation and the negative impact on yields remained until two seasons after the irrigation deprivation. These carry-over effects were particularly accentuated in the treatments in which irrigation was concentrated early in the season. A conference report by Shackel et al., 2011, also on the cv. Non Pareil, described an experiment conducted in the Sacramento Valley of California which applied a control FI (983 mm), two DI treatments (127 mm and 254 mm) and a rainfed treatment, all distributed along the season. That work confirmed the results obtained by Goldhamer and Smith (1995) regarding the negative impact of severe water stress on kernel yield and its carry over effects in subsequent seasons. Shackel et al. (2011) reported that their rainfed treatment reached stem water potential (SWP) values between -2.9 and -6.3 MPa with an important increase of canopy dieback.

Several issues might limit the validity and applicability of the results obtained in the previous studies for the conditions of other Mediterranean-type regions. First, the study of Goldhamer and Smith (1995) applied in all the irrigation deprivation treatments an irrigation water of 406 mm plus 107 mm in pre-season, a water depth which is higher than even the usual amounts used for irrigation in other Mediterranean-type regions, and much higher than the water allocation supplied during severe droughts. Furthermore, both studies (Goldhamer and Smith 1995; Shackel et al. 2011) were conducted using Nonpareil, a soft-shell cultivar widely used in USA and Australia, while almond orchards in Spain and other Mediterranean countries are planted with hard-shell cultivars, coming from a different breeding line (Pérez de los Cobos et al. 2021). Given the prospects for severe water scarcity in the Mediterranean region, it would be desirable to characterize the response of irrigated almond orchards to a single season of severe water deprivation in the event of a drought. We hypothesise that, although almond has been considered a drought-tolerant species in the past (Castel and Fereres 1982; Ruíz-Sánchez et al. 1993; Torrecillas et al. 1996), sudden irrigation deprivation for a season in previously well-watered almond orchards can produce severe water stress conditions jeopardizing the economic viability of the orchards and even tree survival. The objectives of the present study were to (a) investigate the physiological responses and (b) tree survival to different water stress levels imposed during a single-season of severe irrigation water deprivation and, (c) determine their short- (in the season of the stress) and long-term (subsequent seasons) effects on yield.

Material and Methods

Experimental site

The experiment was performed in an experimental 5.5-ha almond orchard [*Prunus dulcis* (Mill) Webb cv. Guara grafted onto GF-677 rootstock] planted in 2009 at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37º 51’ 3’’N, 4º 48’ 38’’ W). Climate is the typical Mediterranean, with hot and dry summers, mild winters, and rainfall averaging 600 mm, concentrated from October to April. The soil is of alluvial origin, with a sandy loam texture and more than 2 m deep. The upper and lower limits of soil water storage are 0.23 and 0.08 cm^3 cm^{-3}, respectively. Tree spacing was 7 x 6 m (238 trees ha^{-1}). Training was done in the first two years to 3-4 scaffolds and then no pruning was performed again. Pest and diseases control were done according to a treatment-calendar adjusted according to weather conditions. Weeds were controlled by combining mowing and herbicide applications. Mineral fertilization was calculated and applied following the recommendations of the California Fertilization Guidelines for Almonds (https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Almonds.html). The irrigation system consisted of two drip irrigation laterals, spaced 1 m from the tree rows, with pressure compensating emitters of 4 l h^{-1}, spaced at 1 m (which makes for 12 emitters per tree). All the trees in the orchard were irrigated to satisfy their full water requirements since planting until the experiment in 2017.

During the study, meteorological data were obtained from an automated weather station installed 300 m apart from the experimental site.

Experimental design

The experiment was initiated in 2017 and tested three differential irrigation treatments, including a rainfed (RF) and a deficit (DI) treatments, plus a full-irrigated control. After that, in 2018 and 2019 full irrigation was restored to all treatments. Briefly, the irrigation treatments were as follows.

- **Control Full Irrigation (FI)**

Trees in this treatment received the irrigation amount required to match the full orchard water requirements (ET_C) as described by López-López et al. (2018b) and following the procedure used in the FI treatment of Moldero et al. (2021). Therein, irrigation was calculated as the sum of transpiration (T) and evaporation from the wetted soil surface (E_{SW}). T was calculated using the relationship between ground cover (GC) and a transpiration coefficient ($T = K_T \cdot ET_0$ where $K_T = 1.2 \cdot GC$) proposed by Espadafor et al. (2015) and used in López-López et al. (2018c). Evaporation from soil (E_S) was dynamically estimated along the season using the model of Bonachela et al. (2001). For the calculations, it was assumed that trees intercepted 70% of solar radiation, which was the average value for the FI treatment in 2017 based on measurements of GC and midday solar radiation interception. The soil fraction wetted by emitters was estimated as a function of irrigation duration, and it ranged from 10% under low evaporative demand to 40% in the high evaporative demand period. Deep percolation was minimized by delaying the onset of irrigation in early spring, which allowed the trees to deplete some of the subsoil water accumulated due to winter precipitations.

Irrigation was scheduled on a biweekly basis to match the balance between ET_C minus effective precipitation (P_{eff}), where P_{eff} was considered to be equivalent to precipitation, assuming no runoff and negligible deep percolation.

- **Deficit Irrigation (DI)**

In this treatment, trees regularly received 25% of the irrigation supplied to FI throughout the 2017 season. To do so, the original irrigation system, with two irrigation laterals with pressure compensating emitters of 4 l h^{-1} spaced at 1m, was replaced by one irrigation lateral with pressure compensating emitters of 2 l h^{-1} before starting the 2017 irrigation season. There are two options to reduce applied water in drip irrigation: either reduce the number of emitters or reduce irrigation time. When the restriction is severe (25% of control), reducing irrigation time with the same number of emitters would lead to high direct evaporation losses which would be excessive for the low application level, as predicted by Bonachela et al., (2001) model. Therefore, the number of emitters was decreased by using one drip lateral instead of two to achieve the 25% application level.

In 2018 the original irrigation system was restored and during 2018 and 2019 the irrigation program was the same as in the FI treatment.

- **Rainfed (RF)**

This treatment did not receive any irrigation water during the 2017 season. In 2018 the original irrigation system was restored and during 2018 and 2019 the irrigation program was the same as in FI treatment.

Table 1 presents the values for irrigation (IR), effective precipitation (P_{eff}) and potential evapotranspiration (ET_0), for each treatment and year, all three computed for each growing season. P_{eff} since bud break to total defoliation of RF trees, during 2017, was around 100 mm. Annual rainfall during 2016 and 2017 (January to December) was 675 and 416 mm, respectively.

Table 1 Seasonal irrigation (IR), effective precipitation (P_{eff}) and seasonal reference evapotranspiration (ET_0), in mm, during the irrigation seasons of 2017, 2018 and 2019. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

Year	Treatment	IR	P_{eff}	ET_0
2017 (7 March - 13 Nov)	FI	764	230	1235
	DI	191		
	RF	0		
2018 (15 March - 11 Nov)	FI	772	384	1086
	DI	772		
	RF	772		
2019 (12 March - 8 Nov)	FI	985	99.6	1181
	DI	985		
	RF	985		

The experiment had a completely randomized design with 7 replications per treatment. Each replication consists of an experimental plot, composed of three rows and three or four trees per row. Only the central trees, named experimental trees, in each plot (one or two trees per plot, depending on plot size), were used for experimental measurements and the rest served as guard trees. Summing up, FI was composed of 13 experimental trees while DI and RF were composed of 11 and 13 experimental trees, respectively.

Ground cover

Growth of each experimental tree was determined by measuring ground cover (GC; %). A single measurement was taken each year (2017 and 2018) in May. The diameter of the canopy horizontal projection was measured at eight different radii ($R_{1\text{-}8}$), 45° apart, using a tape measure in order to document the variability due to the irregular shape of the canopy horizontal projection. Ground cover was calculated as the area of the circle determined bythe average of the eight radii divided by the area allocated to each tree with the following equation:

$$GC\ (\%) = \frac{\pi \cdot (\bar{R}_{1-8})^2}{row \cdot tree\ spacing} \cdot 100 \qquad (1)$$

Tree water status

Stem water potential (Ψ, MPa) was generally measured every week from April to October during 2017 and once a month in 2018 and 2019. Measurements covered the whole irrigation season and were taken on two covered leaves per tree in all central trees per experimental plot. A pressure chamber (Soilmoisture Equipment Corp, Model 3005F01, Santa Barbara, CA, USA) was used. Leaves were selected near the trunk or a scaffold-branch and were covered with aluminium foil for at least 30 minutes before the measurement was taken around solar noon.

Defoliation

During 2017, the canopy defoliation was monitored over time by periodical evaluations from June to October (seven evaluations in total). Defoliation (D) was assessed by estimating the percentage of the defoliated surface of the tree canopy using a 0-4 rating scale. The equivalences between the values of the scale and the percentage of tree canopy defoliation were approximately: 0 < 20%; 1 = 21-40%; 2 = 41-60%; 3 = 61-80%; 4 ≥80%.

Mortality

Trees that did not sprout during spring 2018 were considered dead.

Yield and yield components

Yield determinations were made using the same procedure as in López-López et al. (2018b). Harvest took place around the mid-August and each experimental tree in every treatment plot was manually harvested. De-hulling was done mechanically in the field. Then total in-shell fresh weight (FW, kg) was measured and a randomized sample of 1-2 kg of in-shell nuts was taken per tree (FW_{sample}) from which the tree fruit load, equivalent to number of nuts per tree, was estimated as:

$$Fruit\ load = FW \cdot N_{SAMPLE}/FW_{SAMPLE} \tag{2}$$

Where N_{sample} and FW_{sample} being the number of fruits and fresh weight of the sample. Afterwards, 100 in-shell nuts were randomly chosen from the sample and oven-dried at 70°C until constant weight for estimating the averaged kernel dry weight (kernel weight, g). Kernel yield (Y_{DW}, kg ha^{-1}) was calculated as:

$$Y_{DW} = Fruit\ load \cdot averaged\ kernel\ weight \cdot Tree\ density \tag{3}$$

where the Tree density is the number of trees per hectare.

Hull tight determination was made by counting the number of hull tight nuts ($N_{HULL\ TIGHT\ SAMPLE}$), considered as nuts with suture unsplit, within the randomized sample of 1-2 kg of in-shell nuts taken per tree. Hull tight (hull tight; %) was calculated as:

$$Hull\ tight\ (\%) = N_{HULL\ TIGHT\ SAMPLE}/N_{SAMPLE} \cdot 100 \tag{4}$$

Statistical analysis

The program Statistix 10 (Analytical Software, Tallahassee, USA) was used to perform the statistical analyses considering the completely randomized design of the experiment. The trees that died as a result of the water stress imposed in 2017 were excluded from the statistical analysis in 2018 and 2019.

RESULTS

On-year irrigation restrictions effects (2017)

At the start of the study in May 2017 FI trees were slightly smaller than DI and RF trees. These differences were determined by the random choice of the treatments and were small and far from the statistical significance (Figure 1).

Although the no significant differences between treatments in tree size (~60% of GC) at the start of the experiment (Figure 1), the different irrigation amounts applied to FI (764 mm), DI (191 mm) and RF (0 mm) induced very different Ψ patterns among treatments along 2017 (Figure 2). Ψ differences started early in the season and reached the maximum at the end of July. FI treatment had Ψ around -1.0 MPa for most of the season, only reaching lower values (-1.47 MPa) during the harvest period when irrigation was briefly interrupted to facilitate mechanical harvest. In the DI treatment, Ψ measurements gave similar levels to those of FI until mid-May, but then Ψ decreased rapidly reaching values of -3.3 MPa at the end of July. After that, Ψ partially recovered to around -2.0 MPa by the first two weeks of August, coinciding with a period of defoliation (Figure 3), and remained at a similar level for the rest of the season. Regarding RF trees, Ψ values were similar to those measured for DI and FI until mid-May and then decreased sharply, reaching -4.0 MPa at the end of July. At that time, RF trees were completely defoliated which hampered subsequent Ψ measurements. Indeed, it was only possible to measure Ψ in two trees that retained a few leaves (open triangles in Figure 2). Overall, FI showed significantly higher values of Ψ as compared to DI and RF when the measurements were averaged for the pre-harvest or post-harvest periods, or for the whole measurement campaign. Statistical differences were also found between DI and RF for the same periods, the latter exhibiting the lowest values (Table 2).

The sharp Ψ decrease observed in DI and RF resulted in the partial or total tree defoliation (Figure 3). Leaf shedding in RF trees occurred rapidly after the start of the season, reaching defoliation scores around 4 (i.e. >80%) by the second fortnight of July and complete defoliation by the middle of August. Only one experimental plot formed by two trees exhibited a slower pattern of defoliation, even though they also reached severe defoliation levels of over 75% by the end of the season in mid-October. DI also induced considerable leaf fall, but to a lesser extent than in RF. In the DI treatment, maximum defoliation scores were around 1.5 (i.e. ~50%), in the middle of September after which a slight recovery was noted due to tree resprouting in early autumn. On the other hand, defoliation scores for FI trees were always 0, implying negligible leaf shedding until the season ended in autumn.

Table 4 reports that kernel yield for the FI treatment in 2017 was 2244 kg ha^{-1}, while yield values were 33.5% and 35.8% lower for DI and RF, respectively. These lower kernel yields were directly related to significant reductions in kernel weight in DI and RF, as there were no significant differences in fruit load among treatments (Table 4). Water stress during 2017 also caused a devaluation of the harvest in DI and RF, as many fruits were hull tights (Goldhamer and Smith 1995). Almost all the RF (97%), and most of the DI (74%) production was formed by hull tights, while no hull tights were observed in the FI trees. The fraction of hull tight almonds was related to the level of water stress during the kernel-filling period. A strong sigmoidal relationship between such a fraction and Ψ was found according to which Ψ values below -2.0 MPa lead to a dramatic increase in the proportion of hull tights (Figure 4).

Finally, the total irrigation cut-off performed in the RF during 2017 caused the mortality of 92% of the trees under this treatment, as they did not regrow in 2018. None of the FI and DI trees died during the three experimental years (Table 3).

Long-term irrigation restrictions effects (Carry-over effects)

GC measures taken in 2018 revealed slightly higher values (without statistical significance) to those determined for each treatment in the spring of the previous season for both FI and DI treatments. Despite water stress, the vegetative growth of DI trees during 2017 was not affected because water stress developed after the main growth flush, which normally occurs during spring in almond. In addition, water stress did not cause branch losses as in RF treatment. For that reason, DI trees again maintained their largest size compared to FI during 2018, but again the differences between them were not statistically significant. By contrast, the only RF tree surviving the irrigation cut-off, applied in 2017, showed lower GC values in 2018 (52%) than in 2017 (63%) (Figure 1) due to branch losses resulting from severe stress.

The full irrigation applications to meet ET_C in all treatments resulted in no statistical differences in Ψ among them in 2018 and 2019. In 2018 and 2019, all treatments showed Ψ values ranging from -0.7 MPa to -1.06 MPa (Figure 2).

In 2018, kernel yield in the DI treatment was 14% lower than in FI, but such a difference was not significant. The only tree survivor of the RF treatment only produced 32 kg ha^{-1}, by far the lowest kernel yield among the three treatments. Contrary to 2017, there were no differences between treatments in kernel weight and yield reductions were mostly caused by a lower number of fruits. In 2019, no statistical differences between FI and DI yields were found. Regarding the only survivor of the RF treatment, kernel yield in 2019 was still far below the values observed for FI and DI for the second successive season (Table 4). Kernel weight was similar for FI and DI treatments, 1.24 and 1.18 g respectively, while RF had a much lower value of 0.76 g. The number of fruits increased in the RF tree in 2019 (4852 fruits tree^{-1}) in relation to the previous season (186 fruits tree^{-1}), but it was still far behind the crop load recorded for the same tree in 2017 or for FI and DI, regardless of the season (>7000 fruits tree^{-1}). It should be pointed out that during 2018 and 2019, the number of hull tights was negligible in all treatments.

Averaging the three years, FI showed the highest kernel yields, followed by DI and RF. Statistical tests revealed that the differences among treatments were always significant, regardless of the pair compared. Kernel weight and fruit load showed the same pattern as kernel yield with significantly higher and lower values for FI and RF, respectively.

Table 2 Average Ψ (MPa) of the three treatments for the season 2017 divided into periods: pre-harvest (DOY 137-212); post-harvest (DOY 229-296); season (DOY 137-296). Each value represents the average of all the measurements taken in each period. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

Treatments	Pre-harvest	Post-harvest	Season
FI	-0.93 a	-1.02 a	-0.98 a
DI	-2.17 b	-2.07 b	-2.10 b
RF	-2.60 c	-2.96 c	-2.76 c
P	*<0.001*	*<0.001*	*<0.001*

Completely randomized ANOVA P values are shown for each period and treatment. Means followed by a common letter are not significantly different by the LSD test at the 5% of significance.

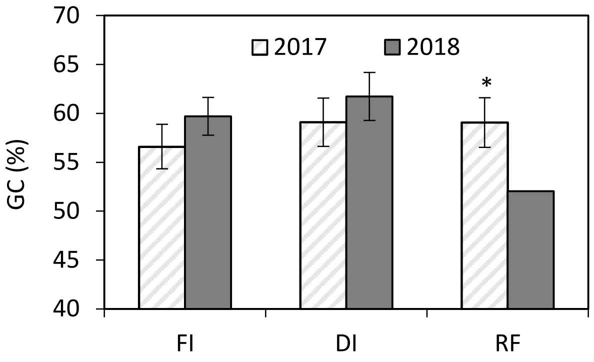

Figure 1 GC for 2017 and 2018. The measurements were done in May of each year. Vertical error bars are the standard error of the means. The asterisk shows the GC of the only RF tree survivor after 2017. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

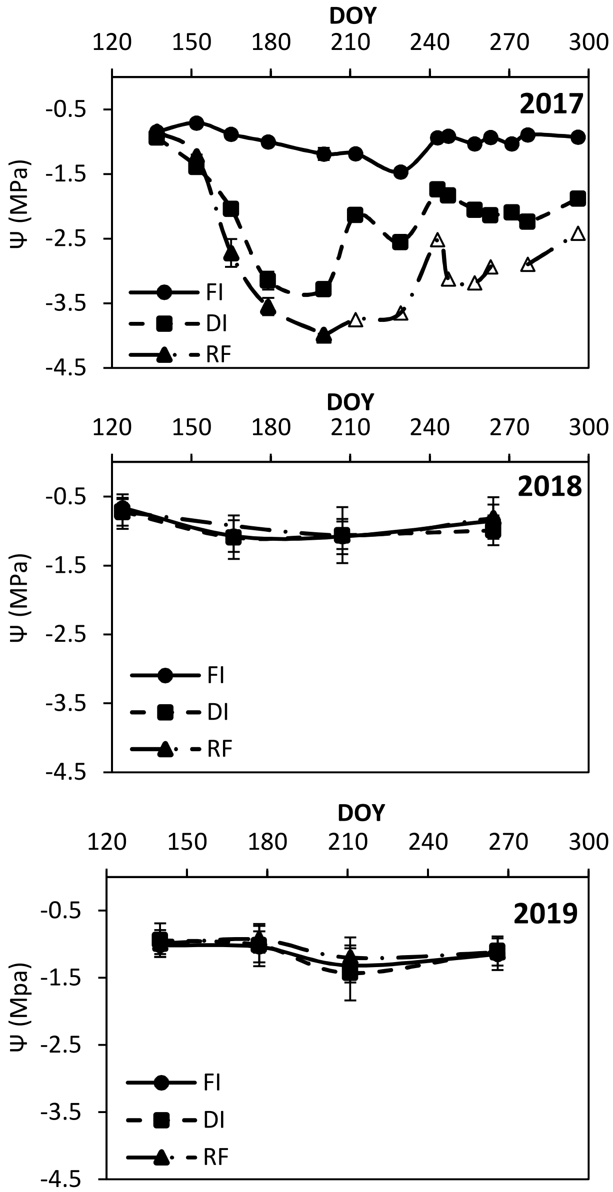

Figure 2 Time course of Ψ(MPa) for 2017, 2018 and 2019 seasons. Each data point is the average of two leaves on all experimental trees in each treatment. Open triangles showed Ψ of the only two RF trees that maintained some leaves after DOY 200. Vertical error bars are the standard error of the means. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

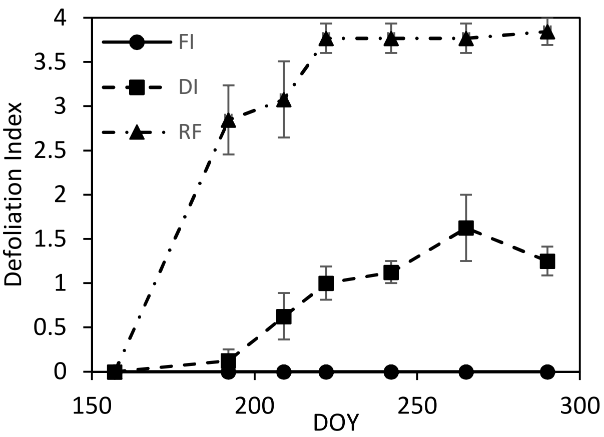

Figure 3 Time course of Defoliation index during 2017 in the three treatments. Vertical error bars are the standard error of the means. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

Table 3 Number of experimental trees, number of trees alive and dead after the 2017 season and their mortality rate for each treatment. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

Treatment	n	Alive	Dead	Mortality rate (%)
FI	13	13	0	0
DI	11	11	0	0
RF	13	1	12	92

Table 4 Dry weight kernel yield and yield components (fruit load and kernel weight) over the three years of study (2017-2019) and their average. Data showed for the years 2018, 2019 and the average for Rainfed treatment was calculated with the data corresponding to the only tree survivor. FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

Yield and yield components	Treatment	Year			Average
		2017	2018	2019	
Kernel yield (kg ha^{-1})	FI	2244 a	2430 a	2318 a	2331 a
	DI	1493 b	2083 a	2124 a	1900 b
	RF	1440 b	*32	*1303	*925
	P-value	*<0.0001*	*0.1659*	*0.2915*	*0.0004*
Kernel weight (g)	FI	1.32 a	1.24 a	1.15 b	1.20 a
	DI	0.88 b	1.18 a	1.29 a	1.07 b
	RF	0.78 b	*0.76	*1.13	*0.89
	P-value	*<0.0001*	*0.2986*	*0.0439*	*0.0016*
Fruit Load (Nº tree^{-1})	FI	7220	8430 a	8499 a	8049 a
	DI	7234	7355 a	7020 a	7203 b
	RF	7786	*186	*4852	*4275
	P-value	*0.5682*	*0.3212*	*0.0883*	*0.0312*
Hull tights	FI	0 a	0	1	0 a

(%)	DI	74 b	0	1	25 b
	RF	97 c	*0	*0	*32
	P-value	*<0.0001*		*0.6637*	*0.0011*

Completely randomized ANOVA P values are shown for each year and their 3-year average. Means followed by a common letter are not significantly different by the LSD test at the 5% level of significance. *Data reported for the only tree that survived in the Rainfed treatment.

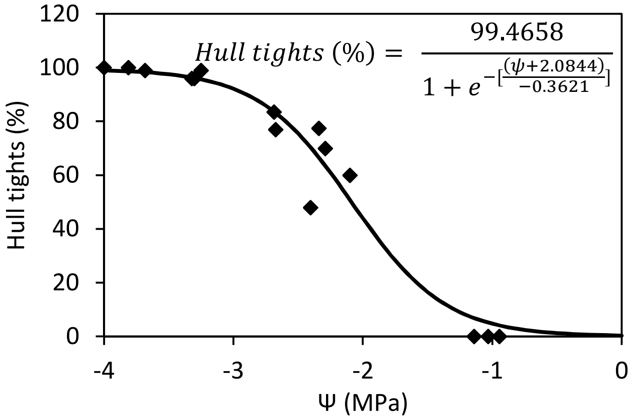

Figure 4 Hull tight nuts (%) against average Ψ measured during kernel-filling stage (DOY 165-225). Each point corresponds to the average values of each experimental tree during the year of stress (2017). The solid line shows the best-fit expression (R^2=0.96; P < 0.0001).

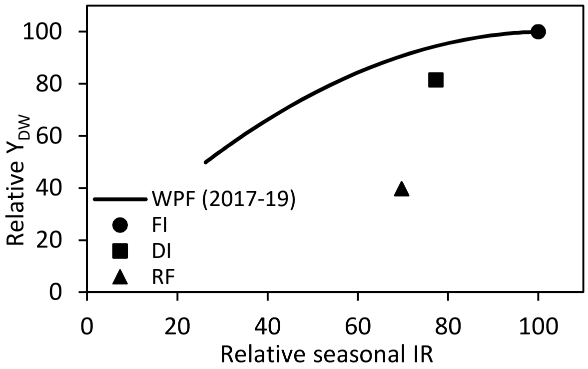

Figure 5 Mean annual kernel yields expressed as dry weight (Y_{DW}) against seasonal irrigation (IR) for FI, DI and RF treatments) and the production function for 2017-2019 (Moldero et al. 2021) represented by the solid line. Data points are the average of three years (2017-2019) of each treatment. All data are presented in relative terms (Rel Y_{DW}-Rel IR). FI: Full Irrigation; DI: Deficit Irrigation; RF: Rainfed.

DISCUSSION

Tree survival

The most remarkable result of the present study is that, despite of the reputation of almond as drought resistant (Castel and Fereres 1982; Ruíz-Sánchez et al. 1993; Torrecillas et al.

1996), total irrigation cut off during one season resulted in the mortality of 92% of trees of a mature almond orchard (cv. Guara) that had been previously cultivated under ample irrigation supply. Risk of almond tree death is a threat that may occur under severe irrigation water restrictions in the event of a drought if water authorities cannot supply even a small fraction of seasonal water requirements. Such a grim scenario is recurrent in southern Spain as a consequence of the water scarcity and the severe and persistent droughts that occur in the region with some periodicity.

The high tree mortality observed in RF was unexpected because of both the presumed water stress resistance of almond and the relatively high depth and water holding capacity of the soil where the study was performed. While soil water content was not measured in this experiment, root zone available water at the beginning of the 2017 season was more than 200 mm, according to neutron probe measurements performed in another block of the same experimental orchard (Moldero et al. 2021). Effective precipitation before the total defoliation of trees was estimated as 100 mm, which implies that RF trees had around 300 mm at their disposal to uptake and use as ET (~25% of seasonal ET_C of a fully irrigated orchard). Such an ET_C estimate is clearly above the 150-200 mm (~15% of seasonal ET_C) suggested by Shackel et al. (2011) as the almond ET survival threshold in their work performed in California with the cv. Non Pareil. The differences between Shackel et al. (2011) findings and those of the present study may be attributed to several factors. For instance, Ψ measurements in RF trees revealed a very fast decline in tree water status, contrary to the gradual development of water stress observed by Shackel et al. (2011). The rate of development of water stress during the season might be critical for the survival of trees, as the lack of the necessary time may have prevented experimental trees to acclimate to the severe water stress conditions (Fereres et al. 1982; Goldhamer and Smith 1995). By contrast, the DI trees of the present experiment received sufficient water to survive, shedding part of the leaves to avoid excessive dehydration levels, as shown in its seasonal Ψ trajectory (Figure 2). One important consideration is that the experimental trees had developed large canopies in previous years under localized irrigation and had never experienced moderate to severe water stress in previous seasons. In that situation, Espadafor et al. (2018) observed a positive response to increased wetted soil volume, suggesting that the drip irrigation system used in the orchard kept the root system relatively confined, and this, together with the large tree size, might explain the fast rate of water stress development, leading to tree death. Additional factors could be the severe evapotranspiration conditions of the 2017 summer and the predisposition of severe water-stressed trees to biotic factors such as bark beetle attacks which could favour tree mortality. As a final remark, cultivar differences in the response to severe water stress may explain the contrasting results reported in Shackel et al. (2011). In the present study, cv. 'Guara' was totally defoliated at -4.0 MPa and trees were not able to re-sprout in the next season. By contrast, cv. Nonpareil survived after undergoing Ψ of -6.0 MPa (Goldhamer and Viveros 2000; Shackel et al. 2011), performing better than 'Carmel' and 'Monterrey' cultivars as reported in Shackel et al (2011). It appears that there is genetic variability among almond cultivars in their responses to severe water stress, a topic which deserves further research.

In season effects of water stress on yield

The deprivation of irrigation in RF and DI in 2017 resulted in yield reductions in proportion to the severity of water deficits. No differences in fruit load existed among treatments, so the decrease in yield observed for DI and RF was exclusively caused by reductions in kernel weight. This was the consequence of the occurrence of water stress during the kernel-filling stage as previously reported in other studies (Goldhamer and Viveros 2000; Girona et al. 2005; Egea et al. 2010). Fruit load had been determined during the post-harvest period of the previous season when all treatments were subjected to the same irrigation schedule (Hutmacher et al. 1994; Goldhamer and Viveros 2000; Esparza et al. 2001; Girona et al. 2005; Egea et al. 2010). Nut shedding was not observed in 2017 in any of the treatments, probably because water stress was developed after the initial and more critical stage of rapid growth (Fereres et al. 1982; Girona et al. 1997; Esparza et al. 2001). In the case of the DI treatment, there could have been effects on the root system of the change from two drip lines to one as a result of imposing the severe DI regime (25% of control). Under the experimental conditions of substantial winter rainfall and deep soils, the root system of drip-irrigated orchards evolve from having a generalized root water uptake pattern to concentrate the water uptake preferentially in the wetted volumes of the emitters, as the rest of the soil dries. Unfortunately, there is no information on root system dynamics to speculate what could have been the specific impact of the drip system change.

All in all, the results obtained have implications for the assessment of the impact of severe water deficits on almond production in the future. Firstly, the experiments should encompass various seasons in order to capture the long-term responses following the severe water deprivation. In this regard, even the RF trees that died in the study produced a rather high amount of nuts in the year of the irrigation cut off. Second, fruit load in almond is influenced by the water status during the previous season, so it would seem advisable in some cases to discard the data obtained during the first year of application of the experiments because they are not totally attributable to the treatments applied (López-López et al. 2018b).

Additionally, they were observed in-season negative effects of water stress on yield quality due to the formation of hull tights. Data suggest a sudden increase in the proportion of hull tights in cv. Guara when the average Ψ remain below -2.0 MPa during the kernel-filling period. Even if the kernel-filling stage was identified as being less sensitive to water stress (Goldhamer and Smith 1995; Goldhamer and Viveros 2000; Goldhamer et al. 2006; Goldhamer and Girona 2012), the analysis performed suggests that deficit irrigation strategies should avoid excessive water stress during that period to obtain good kernel quality and subsequent profits.

Carry-over effects of water stress on yield

Results indicate that the impacts of severe water stress on yield were extended beyond the season when the irrigation cut-off is applied, even if irrigation is re-established, which is in agreement with previous reports (Goldhamer and Smith 1995; Goldhamer and Viveros 2000). The carry-over effects on the productivity of the DI and RF treatments were principally attributed to the decline in fruit load caused by the negative effects of water stress on spur differentiation during the post-harvest period (Fereres 1981; Girona 1997, Esparza 2001), and to a possible increase of premature spur mortality. The intensity and durability of the carry-over effects seem to be directly related to the severity of water stress. Ψ measurements in the only tree which survived in the RF treatment indicate that the occurrence of persistently low Ψ values (below -3.5 MPa) can produce long-lasting effects on yield that may be attributed to a massive spur mortality induced by desiccation during such period of severe water stress. Slight carry-over effects were also noted in the DI treatment, but the impact of the water stress imposed in 2017 (seasonal average Ψ of -2.0 MPa) was not sufficient to induce a significant yield reduction in subsequent seasons in relation to FI. In this case, the decline in spur population presumably induced by water stress might have been partly compensated by an increase in fruit set in 2018 and 2019, although this compensatory mechanism is limited (Kester and Griggs 1959; Tombesi et al. 2017).

Another striking observation which needs to be confirmed was the considerable lower kernel weight in 2018 of the RF survivor tree relative to FI and DI, despite the fact that its fruit load was negligible and irrigation was not limited. One could speculate that severe water stress during spurs differentiation may have affected flower bud differentiation, limiting the potential ovary size and hence the future kernel weight. On the other hand, the limited ovary size may be due to the competition with vegetative growth for the scarce tree carbohydrate reserves after a season where photosynthesis was severely limited by water stress.

Cumulative effects on yield

In a previous work performed in another block of the same orchard used in the present study, Moldero et al. (2021) obtained the irrigation water production function from data collected in the same years (2017-2019). When plotting the three-year average yield responses in relative terms for the irrigation treatments applied in the present study, the data corresponding to the FI shown in Table 4 fitted very well the relationship found by Moldero et al. (2021). By contrast, the average yields of DI and RF were far below (24% and 61%, respectively) what would be expected from the production function (Figure 5). A severe restriction followed by two years of ample supply had a lower yield response than if the same total allocation was evenly distributed over the three years (Figure 5). The different yield responses in the two experiments show that cumulative yields over three years do not depend only on the total cumulative irrigation applied, but also on its distribution over the years, with the concentration of water stress in specific years resulting in large reductions in water productivity. This remarkable finding highlights the great importance of timing of occurrence and temporal distribution of water stress and indicates its multiple implications in agricultural water management.

Concluding remarks

This study demonstrates that a complete irrigation cut-off for one season can have devastating effects on the productive capacity of irrigated almond orchards even affecting tree survival. Tree mortality of up to 92% was reached when trees were not irrigated during one season. Additionally, significant carry-over effects on yield were documented two seasons after the resuming full irrigation.

The differences in yield responses between the production function obtained by Moldero et al. (2021) and the results of the present study highlight the importance of the temporal distribution of water stress, showing large reductions in water productivity caused by the occurrence of water stress in one-crop season This is a remarkable finding suggesting that ensuring some irrigation supply in years of severe water restrictions might be more beneficial for farmers than increasing their average water allocation. Such a strategy would avoid the dramatic effects that a drastic seasonal irrigation cut-off has on the productivity and survival of almond orchards.

This study also highlights the importance of developing proactive strategies to prevent irreversible and lasting damage affecting the long-term sustainability of almond plantations. The large capital investments being made face the risk of large losses due to tree death under severe irrigation restrictions. In the future, further studies should be conducted to investigate and document the minimal amount of irrigation required, and the optimal timing of application, to prevent irreversible damage for various cultivars and rootstocks, and different growing environments.

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